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A crowdful of letters: Disentangling the role of similarity, eccentricity and spatial frequencies in letter crowding

Sacha Zahabi, Martin Arguin *

Centre de recherche en Neuropsychologie et Cognition, Département de psychologie, Université de Montréal, Canada

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ABSTRACT

The present study investigated the joint impact of target–flanker similarity and of spatial frequency content on the crowding effect in letter identification. We presented spatial frequency filtered letters to neurologically intact non-dyslexic readers while manipulating target–flanker distance, target eccentricity and target–flanker confusability (letter similarity metric based on published letter confusion matrices). The results show that high target–flanker confusability magnifies crowding. They also reveal an intricate pattern of interactions of the spatial frequency content of the stimuli with target eccentricity, flanker distance and similarity. The findings are congruent with the notion that crowding results from the inappropriate pooling of target and flanker features and that this integration is more likely to match a response template at a subsequent decision stage with similar than dissimilar flankers. In addition, the evidence suggests that crowding from similar flankers is biased towards relatively high spatial frequencies and that crowding shifts towards lower spatial frequencies as target eccentricity is increased.

1. Introduction

Visual crowding refers to the difficulty of accurately identifying a peripheral visual stimulus when it is flanked by other items. The currently accepted account of crowding assumes that target features are normally detected independently from flanker features, provided that the distance between them is sufficiently large (Levi, 2008). However, when the target–flanker distance is too short, features from both items fall within the same integration fields. Target and flanker features then become difficult to segregate, which interferes with target identification (Pelli, Palomares, & Majaj, 2004). Given that integration fields increase in size as one goes from the fovea to the visual periphery, eccentric targets are more susceptible to crowding with reduced target–flanker distances. Congruently with this account, Levi (2008) proposed a two-stage model of visual feature processing involving first the detection of simple features (in V1), followed by their integration (beyond V1).

The results from a considerable number of studies have identified three major factors that determine crowding. Thus, the magnitude of crowding is a function of inter-stimulus distance and there is a critical spacing beyond which crowding no longer occurs (Pelli, Palomares, & Majaj, 2004). Also, this critical spacing is directly proportional to eccentricity (Pelli, Palomares, & Majaj, 2004; see also Bouma, 1970). Finally, the more similar the flankers are to the target, the more they affect its identification (e.g. Bernard & Chung, 2011; Chung, Levi, & Legge, 2001; Estes, 1982; Freeman, Chakravarthi, & Pelli, 2012; Hess, Dakin, & Kapoor, 2000a; Kooi et al., 1994; Poder, 2007; Shapiro & Krueger, 1983). For instance, Kooi et al. (1994) have demonstrated, using a task requiring observers to identify the orientation of a T flanked by three other T's, that target–flanker dissimilarity in terms of contrast polarity, depth or orientation improved identification performance (see also Hess et al., 2000a). In the letter recognition domain, Bernard and Chung (2011) have shown that the error rates in the identification of a flanked target letter increase with the shape similarity of flankers (see also Estes, 1982; Krumhansl & Thomas, 1977). Relatedly, Freeman, Chakravarthi, and Pelli (2012) have demonstrated that when an error is made in the identification of a flanked letter, similar flankers are much more likely to be reported than dissimilar flankers.

Letters contain a wide range of spatial frequencies and many recent studies have attempted to determine the range of spatial frequencies that are preferentially used by the visual system to identify letters (Grainger, Rey, & Dufau, 2008). This question has profound implications given that our ability to read a word depends first and foremost on the efficiency of our visual system to identify each letter (Pelli, Farell, & Moore, 2003). Critical-band masking studies have shown that visual noise around 3 cycles/let-

* Corresponding author. Address: Département de psychologie, Pavillon Marie-Victorin, Université de Montréal, C.P. 6128, Succ. Centre-ville, Montréal, Qc H3C 3J7, Canada. Fax: +1 514 343 5787.

E-mail address: martin.arguin@umontreal.ca (M. Arguin).

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ter impairs letter identification performance the most (Majaj et al., 2002; Solomon & Pelli, 1994). This suggests that the optimal spatial frequencies for letter identification are around 3 cycles/letter. Congruent findings were obtained through the contrast thresholds for the identification of band-pass filtered letters (Chung, Legge, & Tjan, 2002). In further support, a study by Fiset et al. (2008), using the Bubbles technique (Gosselin & Schyns, 2001), has revealed that spatial frequencies between 2 and 4 cycles/letter provide the most useful information for letter identification. According to Chung, Legge, and Tjan (2002), these optimal spatial frequencies are determined by the intersection of the contrast sensitivity function of human vision with the spatial frequency content of the stimuli that best discriminates among the letters of the alphabet. Relatedly, an important feature of the range of spatial frequencies that dominate letter recognition is that it shifts towards lower retinal frequencies with increasing eccentricity (Chung, Legge, & Tjan, 2002).

Grainger, Rey, and Dufau (2008) point out that more information useful for letter identification is available in high-pass filtered letters than low-pass filtered ones (Chung, Legge, & Tjan, 2002; Parish & Sperling, 1991). Congruently, low spatial frequencies seem to exacerbate the difficulty in discriminating among visually similar letters; i.e. the letter confusability effect. The confusability value for a particular letter is determined from the error rates of normal observers in a task of single letter identification using very brief displays[1] (see Fiset et al., 2008; for a brief review). With words made of letters with a high confusability value, the word recognition performance of normal readers is significantly deteriorated relative to low confusability content with low-pass stimuli (Fiset, Arguin, & Fiset, 2006; Fiset et al., 2006). In contrast, normal readers are impervious to the effect of letter confusability with normal print or with high-pass or broadband filtered letters. Relatedly, an apparent bias towards low spatial frequencies seems implicated in the particular susceptibility of letter-by-letter dyslexics to the letter confusability effect in their word recognition performance with normal print (Arguin, Fiset, & Bub, 2002; Fiset et al., 2005, 2006).

Few studies have examined the role of spatial frequencies in visual crowding. Hess and his collaborators (Hess et al., 2000a; Hess, Dakin, Kapoor & Tewfik, 2000b) reported that the most relevant spatial frequencies for visual processing are shifted towards higher values under crowded conditions. At the fovea, this effect is entirely explained by a shift in the power spectra of the stimulus but this is not the case in the periphery (beyond 5 deg eccentricity), where an alteration of visual processing must be assumed. Chung and Tjan (2007) presented normal observers with spatial frequency filtered target letters flanked on either side by other letters, with three different levels of spacing. Similarly to Hess et al. (2000a, 2000b), their results show that the visual system slightly shifts its sensitivity to higher spatial frequencies when the target letter is surrounded by flankers, but this effect only occurred at the shortest flanker distance (i.e. 0.8*x*; *x* being the height of letter x for the particular font used, a standard metric in the literature on crowding). They also report that this shift cannot solely be accounted by an alteration of the physical properties of the stimuli, whether they are displayed at the fovea or at 5 deg eccentricity.

Chung, Levi, and Legge (2001) have also manipulated the physical properties of visual stimuli to examine the crowding effect in normal readers. Spatial frequency filtered letters were presented with or without flankers at the fovea or at 5° eccentricity. The dependent variable was the contrast threshold required to identify the target letter. The results showed that shorter flanker distances produce a contrast threshold elevation peak when the spatial frequency content of the flankers is similar to that of the target and that this threshold elevation diminishes with a reduction of spatial frequency similarity. This effect was qualitatively the same at the fovea and at 5° eccentricity.

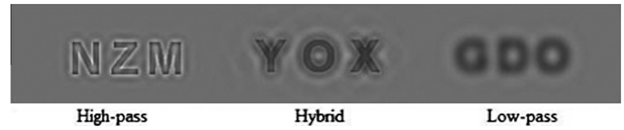

Fig. 1. Examples of filtered letters for the high-pass, low-pass, and hybrid conditions, respectively.

The previous studies examined either the impact of crowding on the spatial frequencies underlying identification performances (Chung & Tjan, 2007; Hess et al., 2000a, 2000b) or how target–flanker similarity, in terms of spatial frequency content, modulates crowding (Chung, Levi, & Legge, 2001). The aim of the present study is rather to examine how the different ranges of spatial frequencies contained in letters interact with letter confusability in a crowding paradigm. More specifically, targets and flankers were presented using one of the following spatial frequency filtering conditions: high-pass, low-pass, hybrid and broadband. In the case of the hybrid filter, the highest and lowest spatial frequencies remained whereas the middle, most useful, frequencies for letter identification were removed. Target–flanker distance was also manipulated, as well as target–flanker confusability.

2. Method

2.1. Observers

Twelve observers, aged between 19 and 23 (3 males and 9 females), with normal or corrected-to-normal vision, took part in the study. They all received monetary compensation for their participation and they were blind to the goals of the experiment.

2.2. Display

Stimuli were presented on a 17-in. DELL monitor with 1024 × 768 resolution at a distance of 57 cm from the observers. The experiment was controlled and programmed using MatLab (MathWorks, Natic, MA) with the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). Stimuli were uppercase 40 pt. Arial letters, subtending 1° of visual angle[2].

Using the Signal Processing Toolbox for MatLab, Butterworth filtering was applied to the stimuli to manipulate their spatial frequency content. The low-pass cut-off was at 1.61 cycles/letter and high-pass cut-off was at 3.14 cycles/letter. Crucially, these cut-off values were matched in terms of the capacity of the residual information (i.e. that remaining in the stimulus after filtering) to support the identification of single uppercase letters, based on the results of Fiset et al. (2008). The low-pass filter let through the low spatial frequencies of the stimulus but blocked those above the 1.61 cycles/letter cut-off. Conversely, the high-pass filter blocked spatial frequencies below the cut-off of 3.14 cycles/letter. The hybrid filter blocked the intermediate spatial frequencies (known to be the most important to support letter recognition) between the two cut-offs. Fig. 1 shows examples of spatially filtered stimuli. A broadband (non-degraded) version of each stimulus was also rendered. All conditions were matched in terms of stimulus

[1] The letter confusability scores were obtained by averaging the uppercase letter confusion matrices published in Van Der Heijden, Malhas, and Van Den Roovaart (1984), Loomis (1982), Gilmore, Hersh, Caramazza, and Griffin (1979), and Townsend (1971). They correspond to the total error rates for each individual letter of the alphabet. These values range between .24 (for the letter L) and .71 (for the letter B), with an average of .47 and a standard deviation of .13.

[2] Available confusability values are for uppercase letters only, thereby preventing the use of lowercase letters in the present experiment.

contrast energy, by equalizing their luminance (62 cd/m^2) and root-mean square contrast (3.0).

2.3. Procedure

Each trial began with a fixation point (+ character in 24 pt. Arial) presented at the centre of the screen. After 500 ms the target letter appeared alone or accompanied by flankers on either side (150 ms duration). After the offset of the letter(s), the fixation point remained until the experimenter entered the observer's response. The inter-trial interval was 500 ms.

Observers received as instructions to identify the target letter as fast and as accurately as possible while keeping their eyes on the fixation point. A vocal key recorded response times. The experiment comprised 36 trials for each of the 64 experimental conditions, for a grand total of 2304 trials per observer. These 64 conditions were established according to four within-subject factors: target–flanker distance (four levels: 1*x*, 1.2*x*, 1.4*x*, and no-flanker; where *x* corresponds to the height of the letter x); target–flanker confusability (two levels: high; low), target eccentricity (two levels: 2.5 and 5 deg), and spatial frequency filtering (four levels: low-pass; high-pass; hybrid; broadband). All letters of the alphabet had an equal probability of serving as the target.

The letter confusability metric was based on an average of letter confusion matrices available from previous studies (see Footnote 1 for details). Low confusability flankers for a particular target were the two letters of the alphabet with the lowest confusability with the target and high confusability flankers were the two letters with the highest confusability.[3] Obviously, the notion of flanker confusability was irrelevant in the no-flanker condition. In that case, the number of trials run was twice that in the other conditions and trials were randomly assigned to either the low or high confusability condition.

The stimuli were presented either above or below the fixation point, in a random order and with an equal frequency of occurrence across trials. For each observer, the experiment was split in three sessions, each comprising 768 trials divided in three blocks of 256 trials each.

The dependent variables were the response latency of correct responses and error rates. While the use of error rates is typical in the crowding literature, that of correct response times (RTs) is not. Our motivation in using the latter is twofold. On the one hand, the literature pertaining to reading commonly uses RTs as its main dependent variable. This is sensible considering that functional reading requires a high level of accuracy and RTs offer a probe into the perceptual/cognitive processes involved in offering this high accuracy. Given that accuracy is relatively high in some conditions of the present experiment, the use of RTs is therefore relevant. On the other hand, while the notion of critical spacing may lead one to conceive crowding as an all-or-none phenomenon (i.e. either the target is totally resistant to the interference of flankers or else, it cannot be identified), this is unlikely to be true. The crowding effects on correct RTs we report below demonstrate that even when a letter can be recognized accurately, it may remain affected by crowding.

3. Results

Data analyses were aimed at revealing crowding effects as a joint function of flanker Distance and Confusability, target Eccentricity, and Filtering. Thus, for both correct RTs and error rates, the measurements obtained without flankers were subtracted from those with flankers in order to uncover the effects of the latter (i.e. crowding effects). For both correct RTs and error rates, crowding effects were analyzed using a four-way within-subject ANOVA with the factors of flanker Distance (four levels: 1*x*, 1.2*x*, 1.4*x*), Confusability (two levels: high; low), Eccentricity (two levels: 2.5°; 5°), and Filtering (four levels: low-pass; high-pass; hybrid; broadband). For the analyses conducted on the crowding effect measured from correct RTs, the Greenhouse–Geisser correction was applied to the degrees of freedom. This was done in order to correct for some variance inhomogeneities that were caused by unequal numbers of trials across conditions, which themselves originate from relatively high error rates in some conditions (up to 75%). Given the magnitude of error rates, they were submitted to an arcsine-square-root transformation prior to data analyses in order to normalize their distribution.

A total of 449 trials (1.6% of all trials) were eliminated from the RTs analysis because correct RTs were more than 2.5 standard deviations from the mean of their condition. The global error rate is of 30.7%. The positive correlation ($r = 0.86$, $p < .001$) between measurements of crowding based on RTs and error rates indicates that there is no speed-accuracy trade-off.

3.1. Response times

Crowding (Fig. 2) was amplified by shorter flanker Distance ($F(1.1,22) = 22.6$; $p < .001$; $\eta^2_\rho = .67$) and greater Eccentricity ($F(1.0,11) = 18.2$; $p < .005$; $\eta^2_\rho = .62$) as well as by high letter Confusability ($F(1.0,11) = 74.6$; $p < .001$; $\eta^2_\rho = .87$). The following interactions were also significant: Distance × Eccentricity ($F(1.3,22) = 5.0$; $p < .05$; $\eta^2_\rho = .31$); Eccentricity × Filtering ($F(2.2,33) = 4.0$; $p < .05$; $\eta^2_\rho = .27$); and Confusability × Eccentricity × Filtering ($F(2.3,22) = 7.9$; $p < .005$; $\eta^2_\rho = .42$). In consequence, the experimental design was broken down into simple effects analyses of Distance × Crowding × Filtering separately for each eccentricity.[4]

At 2.5 deg eccentricity, a significant effect of Filtering was observed ($F(2.6,33) = 8.8$; $p < .001$; $\eta^2_\rho = .45$). However, Filtering inter-

[3] It should be noted that spatial frequency filtering may alter the similarity relations among letters such that the target-flanker confusability values used here, which were obtained with broadband (i.e. unfiltered) letters, may apply imperfectly to spatially filtered letters. To determine this impact, we computed letter confusion matrices by cross-correlating the images of all possible letter pairs in each filtering condition. We then examined how the two most similar and two most dissimilar letters to each letter of the alphabet for the broadband condition ranked in each of the spatially filtered conditions. The results confirm an impact of spatial filtering on similarity relations. The average similarity rankings (1 for most dissimilar; 25 for most similar) for the low confusability letters are 3.1 for low-pass, 7.8 for high-pass, and 3.2 for hybrid (compared to 1.5 for broadband). For the high confusability letters, the average rankings are 23.2 for low-pass, 21.8 for high-pass, and 24.0 for hybrid (compared to 24.5 for broadband). All the differences between the rankings obtained in the spatially filtered conditions and broadband are statistically significant ($p < .05$). This suggests that spatial frequency filtering may have weakened our manipulation of letter confusability by moving the highest/lowest confusability letters to a less extreme position on the confusability continuum. The distinction we make here between flankers with high vs. low confusability with the target remains valid nevertheless, since the inversion of confusability rankings (from low to high confusability, or vice versa) with filtered letters was extremely rare – twice over 156 possibilities. Moreover, had this issue been a major factor in our results, we should have expected a greater sensitivity to letter confusability with broadband filtering than with spatially filtered letters. The observations reported below however, do not support this prediction. Finally, we underline that the alternative to the present manipulation of target-flanker confusability would have been to use distinct letter confusion matrices for each filtering condition, which raises two significant problems. First, to the best of our knowledge, confusion matrices for spatially filtered letters do not exist and to obtain them through empirical testing would constitute a substantial task in itself. Second, this alternative method would imply that the flanking letters used would differ across filtering conditions, which may introduce its own problematic issues.

[4] For the purpose of concision and readability, in reporting simple effects, only new effects or those that qualify the main effects described from the general ANOVA are reported.

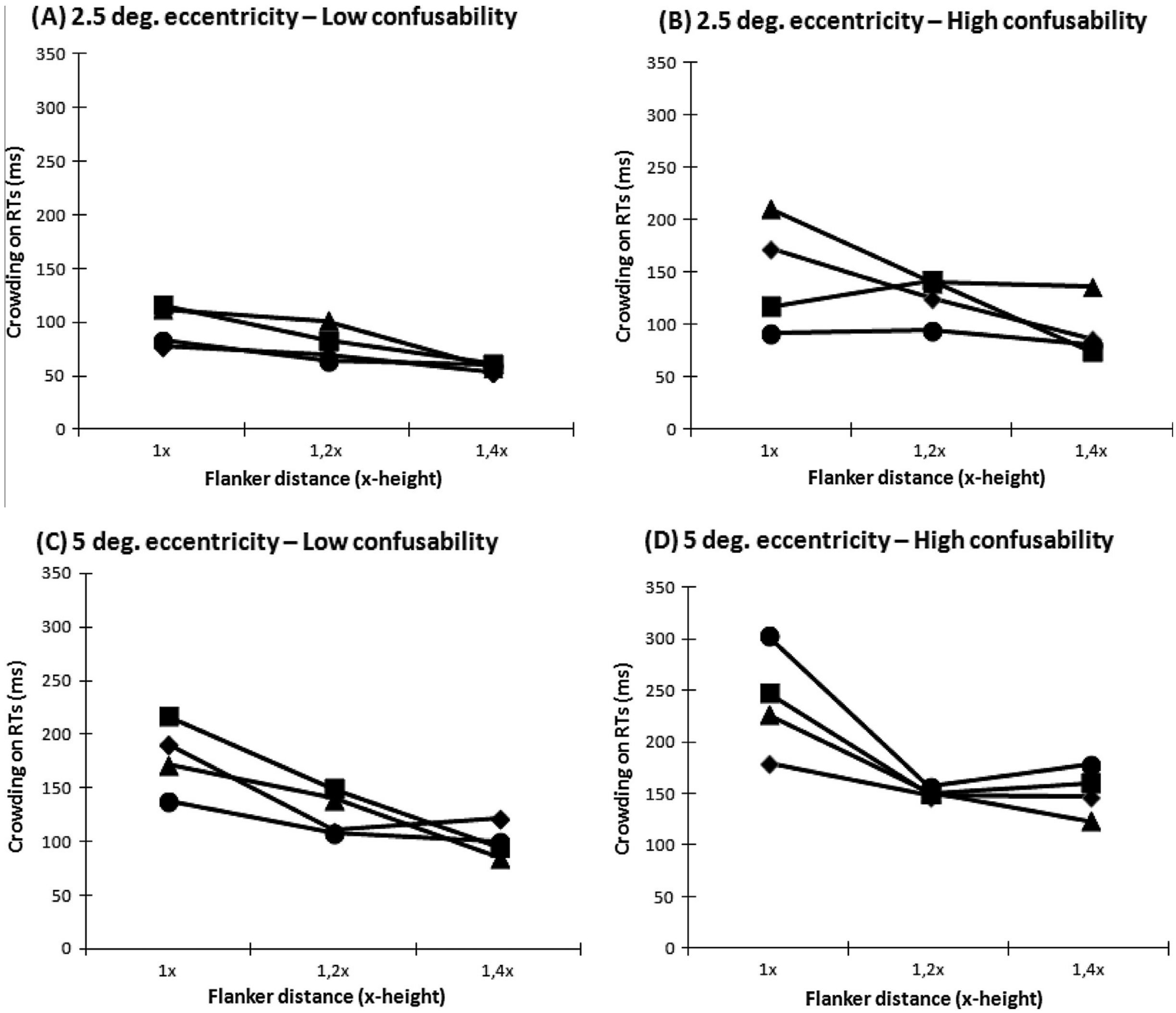

Fig. 2. Crowding as measured from correct RTs as a function of flanker distance. Each panel illustrates the results according to target eccentricity and flanker confusability. Filtering conditions: ● = Broadband; ♦ = High-pass; ■ = Low-pass; ▲ = Hybrid.

acted separately as well as jointly with Confusability and Distance (Confusability × Filtering: $F(1.9,33) = 7.7$; $p < .005$; $\eta_\rho^2 = .41$; Distance × Filtering: $F(3.1,66) = 3.0$; $p < .05$; $\eta_\rho^2 = .21$; Confusability × Distance × Filtering: $F(3.4,66) = 5.7$; $p < .005$; $\eta_\rho^2 = .34$). With low confusability flankers, only the Distance effect was significant (weaker crowding with increasing flanker distance: $F(1.8,22) = 35.1$; $p < .001$; $\eta_\rho^2 = .76$). With high confusability flankers, crowding was weaker with broadband letters than with either the high-pass ($F(1.0,11) = 16.7$; $p < .005$; $\eta_\rho^2 = .60$) or hybrid ($F(1.0,11) = 28.4$; $p < .001$; $\eta_\rho^2 = .72$) filters. Moreover, the effect of Distance was not significant with broadband letters ($F(1.9,22) = 1.4$; *ns*), which contrasts significantly with the other Filtering conditions (all p's < .03, for all interactions). The significant Distance effect with low-pass filtered letters ($F(1.6,22) = 6.6$; $p < .05$; $\eta_\rho^2 = .38$) was weaker than that with either the high-pass ($F(1.6,22) = 4.6$; $p < .05$; $\eta_\rho^2 = .29$) or the hybrid ($F(1.3,22) = 6.0$; $p < .05$; $\eta_\rho^2 = .35$) filters. Finally, the effect of Distance was significant (high-pass: $F(1.9,22) = 26.7$; $p < .001$; $\eta_\rho^2 = .71$; hybrid: $F(1.8,22) = 7.8$; $p < .01$; $\eta_\rho^2 = .41$) and of the same magnitude ($F(2.0,22) = 1.8$; *ns*) in the latter two conditions.

At 5 deg eccentricity, the effect of flanker Confusability ($F(1.0,11) = 79.0$; $p < .001$; $\eta_\rho^2 = .88$), flanker Distance ($F(1.1,22) = 13.2$; $p < .005$; $\eta_\rho^2 = .55$), as well as the Confusability × Filtering interaction were significant ($F(2.2,33) = 3.5$; $p < .05$; $\eta_\rho^2 = .24$). Simple effects of this interaction indicated no significant effect of Filtering for either low ($F(1.4,33) = 1.8$; *ns*) or high confusability ($F(2.1,33) = 1.8$; *ns*) flankers. The key difference in the pattern of crowding effect as a function of Filtering between low and high Confusability flankers pertains to the position of broadband filtering (see Fig. 2). Specifically, whereas the crowding effect is weakest with the broadband filter with low confusability flankers (115 ms vs. 154, 141, and 133 ms for low-pass, high-pass, and hybrid, respectively), it is the greatest with high confusability flankers (213 ms vs. 186, 158, and 167 ms for low-pass, high-pass, and hybrid, respectively).

3.2. Error rates

Crowding as measured from the error rates (Fig. 3) was magnified with flankers that were closer to the target (Distance: $F(2,22) = 226.7$; $p < .001$; $\eta_\rho^2 = .95$), with increased target Eccentricity ($F(1,11) = 117.8$; $p < .001$; $\eta_\rho^2 = .92$), and with high (vs. low) Confusability flankers ($F(1,11) = 36.7$; $p < .001$; $\eta_\rho^2 = .77$). The main effect of Filtering was also significant ($F(3,33) = 18.4$; $p < .001$; $\eta_\rho^2 = .63$), as were several interactions: Confusability × Filtering: ($F(3,33) = 6.4$; $p < .005$; $\eta_\rho^2 = .37$); Distance × Filtering: ($F(6,66) = 8.0$; $p < .001$; $\eta_\rho^2 = .42$); Eccentricity × Filtering: ($F(3,33) = 4.3$; $p < .05$; $\eta_\rho^2 = .28$); Confusability × Distance × Eccentricity: ($F(2,22) = 8.8$; $p < .005$;

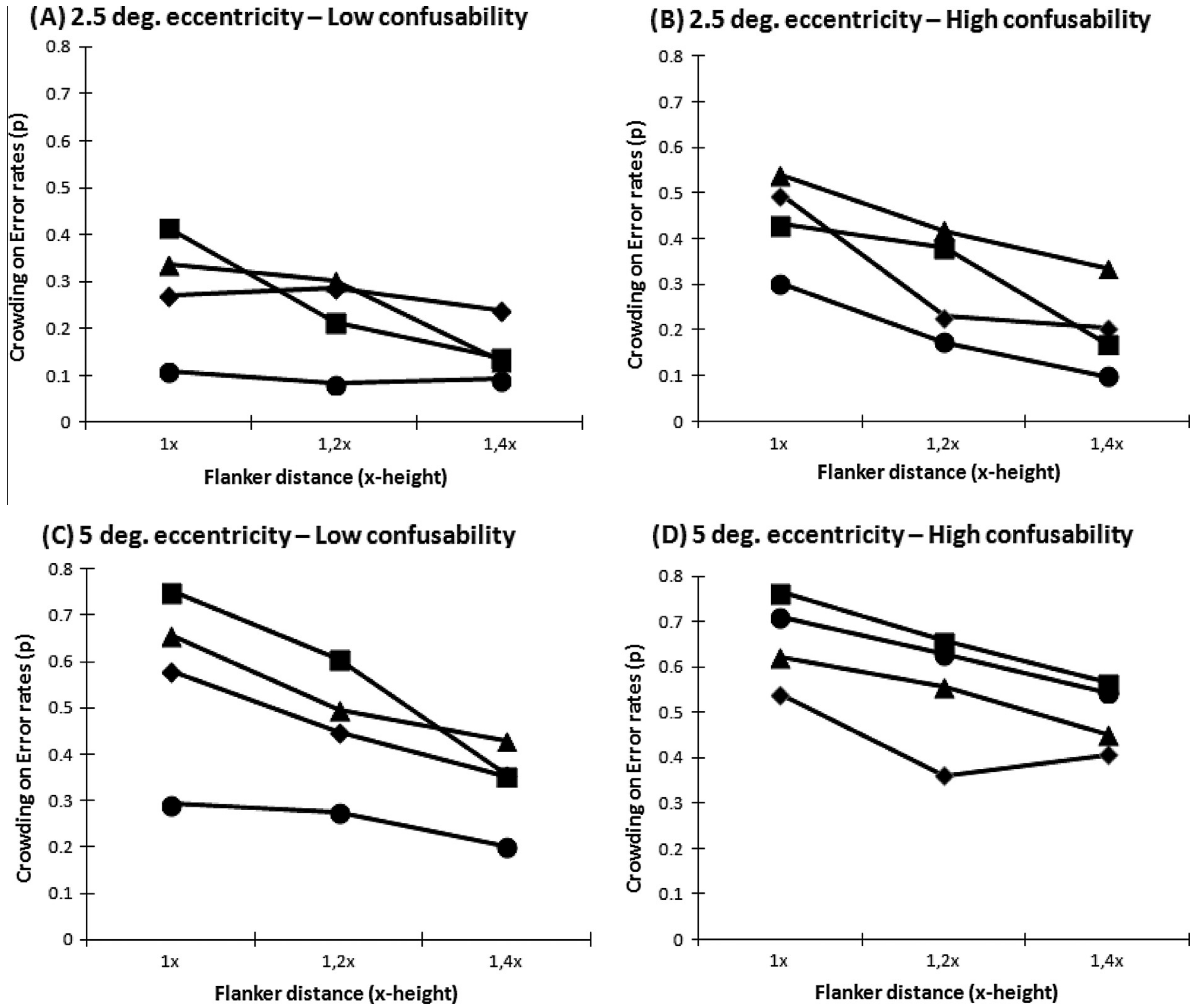

Fig. 3. Crowding as measured from error rates as a function of flanker distance. Each panel illustrates the results according to target eccentricity and flanker confusability. Filtering conditions: ● = Broadband; ♦ = High-pass; ■ = Low-pass; ▲ = Hybrid.

$\eta_\rho^2 = .44$); Confusability × Distance × Filtering: ($F(6,66) = 3.6$; $p < .005$; $\eta_\rho^2 = .24$); Confusability × Eccentricity × Filtering: ($F(3,33) = 11.4$; $p < .001$; $\eta_\rho^2 = .51$).

At 2.5 deg eccentricity, the pattern of effects is complex, with all main effects and interactions significant (all p's < .05), except for Confusability × Filtering ($F(3,33) = 1.3$; *ns*). With low confusability flankers, the effect of Distance was not significant with either broadband ($F(2,22) > 1$) or high-pass filtered letters ($F(2,22) = 1.1$; *ns*) but crowding was greater in the latter condition ($F(1,11) = 11.8$; $p < .001$; $\eta_\rho^2 = .52$). With the low-pass ($F(2,22) = 45.5$; $p < .001$; $\eta_\rho^2 = .81$) and hybrid filters ($F(2,22) = 15.5$; $p < .001$; $\eta_\rho^2 = .59$), the effect of Distance was significant and it was greater in the former than in the latter condition ($F(2,22) = 4.5$; $p < .05$; $\eta_\rho^2 = .29$). With high confusability flankers, the effect of Distance was significant for all filtering conditions (all p's < .005) and it was greater with high-pass filtered letters than with broadband letters ($F(2,22) = 3.6$; $p < .05$; $\eta_\rho^2 = .25$). The shape of the Distance effect differed between high-pass and low-pass filters ($F(2,22) = 7.1$; $p < .005$; $\eta_\rho^2 = .39$) but the overall magnitude of this effect was quite similar. In addition, crowding was greater with the hybrid than with any other filter (all p's < .05) and with the low-pass filter than with broadband ($F(1,11) = 7.4$; $p < .05$; $\eta_\rho^2 = .40$).

At 5 deg eccentricity, all main effects and interactions were significant (all p's < .05). With low confusability flankers, the effect of Distance was significant for all Filtering conditions (all p's < .05). However, crowding as well as the magnitude of the Distance effect differed across filtering conditions. Thus, crowding was weaker with broadband filtering than with any other filtering condition (all p's < .005) and it was weaker also with high-pass than with low-pass filtering ($F(1,11) = 7.8$; $p < .05$; $\eta_\rho^2 = .42$). Distance had a greater impact on crowding with low-pass filtering than with any other filtering condition (all p's < .05). Finally, the Distance effect was greater with hybrid filtering than with broadband ($F(2,22) = 4.7$; $p < .05$; $\eta_\rho^2 = .30$). With high confusability flankers, the Distance effect was significant ($F(2,22) = 37.7$; $p < .001$; $\eta_\rho^2 = .77$) and did not vary significantly according to Filtering ($F(6,66) = 1.7$; *ns*). However, the magnitude of crowding differed between filtering conditions ($F(3,33) = 9.5$; $p < .001$; $\eta_\rho^2 = .47$). Thus, crowding was weaker with high-pass filtering than in any other condition (all p's < .05) and it was worse with the low-pass than hybrid filter ($F(1,11) = 9.5$; $p < .05$; $\eta_\rho^2 = .47$). Notably, crowding did not differ significantly between broadband filtering and low-pass ($F(1,11) < 1$) or hybrid ($F(1,11) = 3.9$; *ns*).

4. Discussion

The results of the present experiment replicate the joint impact of spacing and eccentricity on the crowding effect that alters visual identification performance with peripheral stimuli. The present findings also demonstrate that high confusability flankers amplify crowding relative to those of low confusability. This finding is analogous to the magnification of crowding by visual similarity previously found by others in various processing domains, including letter recognition (e.g. Bernard & Chung, 2011; Chung, Levi, & Legge, 2001; Estes, 1982; Freeman, Chakravarthi, & Pelli, 2012; Hess et al., 2000a; Kooi et al., 1994; Poder, 2007; Shapiro & Krueger, 1983). The present experiment also reveals an intricate pattern of interactions regarding the way the spatial frequency content of the stimuli impact upon crowding as a joint function of flanker distance and confusability as well as target eccentricity.

In all cases but one, when a filtering effect occurred, the condition that was least affected by crowding or by its amplification with shorter flanker distances is broadband. The notable exception is with a high eccentricity (5 deg) target and high confusability flankers, where broadband filtering was about the worst condition with respect to crowding and high-pass filtering is the condition that fared best. These effects are more evident on error rates but they also occur on correct RTs (see Figs. 2 and 3). Regardless of flanker confusability, with high eccentricity targets, it is low-pass filtering that led to the greatest crowding and greatest amplification thereof with short flanker distance, an effect that is particularly apparent on error rates (see Fig. 3). Conversely, crowding is weaker with high-pass filtering than with low-pass at high eccentricity (error rates; Fig. 3), which is not the case at low eccentricity. At low eccentricity, high letter confusability seems to disadvantage letters comprising high spatial frequencies but no intermediate spatial frequencies (high-pass and hybrids; apparent on both RTs and error rates, see Figs. 2 and 3).[5]

In what follows, we offer an account of the various aspects of the present findings which verifies previous proposals as to the mechanisms underlying crowding and adds a crucial notion pertaining to a variation in the spatial frequencies of features that most contribute to crowding according to retinal eccentricity.

4.1. Distance, eccentricity, and confusability/similarity

The joint effects of flanker distance and target eccentricity on crowding find a ready explanation in the notion that crowding is caused by the pooling of features within integration fields with loss of source information (e.g. Bernard & Chung, 2011; Freeman, Chakravarthi, & Pelli, 2012; Levi, 2008; Pelli, Palomares, & Majaj, 2004). Since integration fields become larger with increasing eccentricity and the encroachment of flankers into the integration field of the target is increased by shorter target–flanker distances, the same mechanism accounts for both effects and their interaction.

Feature pooling also offers a straightforward account for the magnification of crowding by the increased confusability/similarity of the flanker to the target under the concept proposed by Bernard and Chung (2011) that a decision stage must follow feature integration to determine the participant's response. The function of this decision stage is to compare the perceptual representation obtained for the target (potentially altered by the deleterious effect of crowding) to templates of all the possible letters. With dissimilar flankers (e.g. X for target O), the erroneous integration of features with the target is unlikely to lead to an acceptable response within the response set available and the representation obtained would thus be rejected at the decision stage. In contrast, the wrongful integration of target and flanker features is much more likely to lead to an acceptable perceptual representation for the decision stage, thereby increasing the error rate with similar flankers.

[5] We have obtained findings congruent with those summarized here in an identical experiment, except for the cut-offs applied for spatial frequency filtering. These cut-offs were selected according to the same principles as applied here except that they were less stringent. Thus, the low spatial-frequency cut-off was set at 1.21 cycles/letter and the high spatial-frequency cut-off was 3.54 cycles/letter.

4.2. Spatial frequency filtering

It may appear unsurprising that overall, the spatial filtering condition that is most resistant to crowding is broadband. Indeed, this is the only condition that fully included the optimal spatial frequencies for letter identification. The fact that broadband letters comprised the richest amount of information apt at supporting letter recognition thus offered some degree of protection against crowding. We suggest that this protection was exerted by raising the threshold at which contamination caused by the wrongful integration of flanker features can divert the decision stage (see above) towards competing letter identities. Alternatively, one might also suppose that the letter features in the optimal spatial frequency range are more resistant to perturbation by crowding than those at non-optimal spatial frequencies, but it is not clear at present why this should be.

Conversely, we found that low-pass filtered letters are the most susceptible to crowding at the highest retinal eccentricity tested here (5°). Low-pass filtered letters are characterized by the fact that they are: 1 – largely deprived of the optimal spatial frequencies for letter identification, and; 2 – deprived of high spatial frequencies, which appear especially important to discriminate among visually similar letters (see Section 1). Following the logic proposed above to account for the resistance of broadband letters to crowding, the susceptibility of low-pass letters would rest on the scarceness of the information they comprise to support letter recognition or, alternatively, to the lesser resistance of these features to perturbation by crowding.

The fact that low-pass filtering did not clearly stand out as the most susceptible condition to crowding with low eccentricity (2.5°) targets may seem incompatible with this account. We note however, that low eccentricity targets shown with high confusability flankers constitutes a special case, where high-pass and hybrid filtering led to a particularly high susceptibility to crowding; an issue we will discuss later. Moreover, with low eccentricity targets, performance with low-pass filtered letters presented on their own (i.e. without flankers) was somewhat weaker than in the other conditions with respect to accuracy (see Table 1). This may have reduced sensitivity to crowding. More importantly, we note a variation of spatial frequency sensitivity according to retinal eccentricity which may have impacted our results in a more fundamental way.

Thus, accuracy for unflanked letters was unaffected by increased target eccentricity with low-pass ($F(1,11) < 1$) and broadband filtering ($F(1,11) = 1.2$; *ns*) whereas it was markedly reduced with the high-pass filter ($F(1,11) = 54.1$; $p < .001$; $\eta^2_\rho = 1.00$) and somewhat less so with the hybrid filter ($F(1,11) = 16.1$; $p < .005$; $\eta^2_\rho = .95$; see Table 1). Similarly, the effect of eccentricity on RTs to unflanked letters (significant for all filtering conditions: all F's$(1,11) > 10.3$; $p < .01$) was substantially weaker with low-pass or broadband than with high-pass or hybrid

Table 1
Correct RTs and percentages of errors for unflanked targets as a function of eccentricity and filtering.

	Correct RTs		Error rates	
	2.5 deg Ecc.	5 deg Ecc.	2.5 deg Ecc.	5 deg Ecc.
Broadband	392	414	3.8	5.4
High-pass	408	477	5.5	19.1
Low-Pass	418	445	8.4	8.4
Hybrid	412	475	4.8	11.4

filters (interaction term: $F(3,33) = 7.2$; $p < .005$; $\eta^2_\rho = .97$). Based on the spatial frequency content of the letters in the different filtering conditions, these observations demonstrate a loss of high spatial frequency information with increasing retinal eccentricity. Some features of the data suggest that this translates into a shift in the range of spatial frequencies that are most involved in crowding according to retinal eccentricity. Thus, as noted above, low-pass letters seem to suffer more (relative to other filtering conditions) from crowding at high than at low retinal eccentricity. The converse seems to be true for high-pass filtering, which was less susceptible to crowding than the other filtering conditions (except for broadband with high confusability flankers, to be discussed below) at high eccentricity whereas this is not verified at low eccentricity. This spatial frequency shift in the crowding effect according to retinal eccentricity also helps understand the following two phenomena that pertain to the joint impact of filtering and high flanker confusability/similarity, which varies markedly across low and high eccentricity.

At low eccentricity and with high confusability flankers, it is high-pass and hybrid filtered letters that suffer from the worst crowding (Figs. 2b and 3b). This contrasts with low confusability flankers, where crowding for these filtering conditions was comparable to low-pass. A common feature of high-pass and hybrid letters is that their useful information content is largely focussed on high spatial frequencies and that they are deprived of the intermediate spatial frequencies that are optimal for letter identification. We argue that their particular susceptibility to high confusability/similarity flankers largely rests on the fact that it is spatial frequencies in the relatively high range that effectively discriminate between visually similar letters (see Introduction). Consequently, when these high frequency flanker features are pooled with those of the target, they have a particular power to generate a perceptual representation that matches a letter other than the target at the decision stage (see above) and thus lead the observer to commit an error.

The notion that crowding shifts towards lower spatial frequencies when target eccentricity is increased accounts for the great susceptibility of high eccentricity broadband letters to high confusability flankers. Specifically, high spatial frequencies generate less crowding at 5 than at 2.5 deg eccentricity, which largely protects hybrid, and especially high-pass letters from crowding (see above). With crowding shifting to a lower spatial frequency range, it is now broadband letters, whose information content is largely focussed on intermediate spatial frequencies, that suffer most from feature pooling with high confusability/similarity flankers.

5. Conclusions

The present study examined the joint effects of target eccentricity, flanker distance and similarity and spatial frequency content on crowding in the context of a letter identification task. The results are congruent with the view that crowding results from feature pooling within integration fields that increase in size with retinal eccentricity. The increased impact of crowding with high similarity flankers is best accounted for by the notion that target–flanker feature pooling is more likely to match a response template at a subsequent decision stage than dissimilar flankers. We also report evidence that the magnification of crowding with similar flankers is biased towards relatively high spatial frequency features and that increased target eccentricity leads crowding to shift towards lower spatial frequencies.

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